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Phase Slips and Josephson Weak Links in Superfluid Helium

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When superfluid ^{4}He flows through a submicron aperture, the velocity is limited by a critical value which marks the onset of quantized vortex creation. The evolution of the vortices causes the quantum phase across the aperture to change by 2π, leading to a detectable drop in flow energy. Recent studies of these phase slip events have provided new insights into the nucleation mechanisms for quantum vortices. By contrast, superfluid ^{3}He passing through a submicron aperture exhibits nonlinear hydrodynamics, characterized by a Josephson-like current phase relation. Recent experiments have revealed a multitude of effects analogous to phenomena observed in superconductors. The experiments also reveal unexpected effects such as bistability, π-states, and novel dissipation mechanisms.

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1. INTRODUCTION

During the past two decades research on the flow of superfluids through small apertures has yielded an expanded understanding of the nature of the Helium macroscopic quantum states. Since recent review articles dealing with phase slippage[1] in ^{4}He and Josephson-like effects[2] in ^{3}He detail the state of our understanding of these phenomena, this article in the Olli Lounasmaa commemorative issue will only very briefly describe the basic observations and give references to the articles that provide a more complete description.

I take this opportunity to present a few personal historical remarks on Olli Lounasmaa's role in the development of this field at Berkeley which is one of the three centers (the others being Saclay and Minneapolis) where much of the recent work has been performed. This narrative provides an example of the way science benefits when a single individual takes the effort to form a hub for the interaction between members of an international

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community in a single field. In this way Olli Lounsamaa's laboratory has played (and continues to play) a role in millikelvin physics analogous to that of Niels Bohr's laboratory in the early days of quantum mechanics. It also exemplifies the way the random walk of science leads from one related topic to another as each newfound answer leads to multiple new questions.

The small aperture work at Berkeley evolved from experiments on the depairing critical velocity in superfluid ^{3}He. In the late 1970's we explored the depairing collapse of superflow when ^{3}He is forced through tubes with diameters on the order of 50 μm. Even our earliest work owed a debt to Olli since our task to enter the field of submillikelvin physics was enormously eased by the completion of the thesis of Olli's student Robert Gylling describing the design and operation of a nuclear demagnetization cryostat. This document reached me in Berkeley in about 1975 through Norman Phillips who had spent a sabbatical year as a visitor in the Helsinki laboratory. The thesis, coupled with a personal assurance of Matti Krusius (another of Olli's coworkers) that "the colder you go the easier it becomes!" helped my student Keith DeConde and me to build our first nuclear demagnetization cryostat. One of our first experiments was to study the depairing critical velocity.[3] That project required us to develop techniques for manufacturing 50 μm diameter flow tubes and the associated techniques for measuring small flow currents.

In 1981 Olli spent six months of his sabbatical as a guest in my laboratory.[4] While in Berkeley he and I designed and tested an apparatus to search for persistent currents on ^{3}He. This quest was motivated by our observations in the flow-depairing experiments that suggested that even subcritical flow exhibited dissipation.[5] That observation turned out to be explained by conventional second viscosity[6] but our lack of understanding at the time led us to doubt if persistent currents would exist in ^{3}He.

Olli and I agreed to a collaborative experiment in which the Berkeley-built persistent current cell would be mounted on the Helsinki ROTA I rotating cryostat for a search for persistent currents. On his return flight to Finland, Olli hand-carried the cell, temporarily housed in a discarded coffee can. We joked about the fact that this contraption looked suspiciously like a bomb. It is unthinkable today that an object with this unusual appearance would be permitted onboard a commercial aircraft! Today, even Olli could not convince the security personal of its innocent nature.

Several months later I came to Helsinki for six months for the purpose of working on this experiment. Olli assigned his student Jukka Pekola to work with me on the project. Jukka had recently completed an experiment with Lounasmaa and his coworkers, searching for acoustically-induced steps in the current-pressure characteristic for ^{3}He flowing through the small pores in nucleopore filter. This was the first reported experiment[7] on the topic of Josephson related phenomena in ^{3}He. Although they found there were no "steps", the work established that Josephson weak links could not have the geometry characterized by nucleopore.

My early collaborative relationship with Jukka was essential for the later weak link experiments in Berkeley. Jukka and I often enjoyed performing order-of-magnitude calculations on the chalkboard. It was an enormous pleasure for me to have a young colleague who was so enthusiastic about exploring new ideas. It was very generous of Olli to support his student and me to work on ideas somewhat peripheral to our stated plans. The symbiotic boost to our individual efforts cannot be understated.

One of the calculations we did was to examine the feasibility of studying flow through a single submicron aperture. Jukka's previous work on nucleopore used millions of parallel apertures whose submicron diameter was comparable to the superfluid ^{3}He coherence length, ξ. This is the length scale that should characterize a Josephson weak link. By contrast the earlier work in my laboratory had focused on a single aperture whose diameter was about 100 times greater than the coherence length. Since a single submicron aperture would yield mass currents 10^4 times smaller than we were accustomed to observe, I would have been reluctant to embark on a project to characterize the flow in such apertures. However, on the chalkboard our estimates indicated that the mass currents could be detectable using the state-of-the-art capacitive techniques which my student Greg Swift had developed for other experiments.[8] At some point Jukka's enthusiasm led us to say: "Let's do it!" Our plan was for Jukka to graduate and later come to Berkeley as a postdoctoral researcher. With Olli's blessing this came to pass.

Shortly before Jukka arrived in Berkeley, Seamus Davis, a new graduate student at Berkeley, joined my group. When Jukka arrived, Seamus and he joined forces to pursue the single weak link experiments. Their collaborative chemistry was outstanding and the work proceeded rapidly, especially when I was absent from Berkeley on a sabbatical. Jukka and Seamus focused on studying the dc flow characteristics of a single weak link. Much to their annoyance I began urging them by letters to change course and pursue a much more speculative quantum interference experiment. I am afraid my enthusiasm for quantum interference overcame my managerial skills to the point where Jukka threatened to leave Berkeley if I persisted in deflecting them from their present direction! The technical success achieved by Jukka and Seamus led to the subsequent generations of Berkeley weak link experiments including, eventually, quantum interference.[9]

The narrative above is to show that the Berkeley weak link experiments were influenced by Olli Lounasmaa through several important contributions.

1. His leadership and commitment to developing practical nuclear refrigeration and making the technology available to the "masses". 2. His vision at a very early stage to search for Josephson effects in nucleopore. 3. His realization of the scientific importance of bringing foreign scientists to his laboratory to interact with and form collaborations with his colleagues. Particularly this latter aspect of Olli's energies surely has been repeated many times over. A large proportion of millikelvin physicists benefited from Olli's hospitality in his laboratory. From these many visits, ideas have been born and exchanged and collaborations have been germinated and blossomed. The state of our knowledge of superfluid systems would be quite different had Olli Lounasmaa not played the active role from which so many of us have benefited.

2. JOSEPHSON WEAK LINKS IN ^{3}HE

In 1962, Brian Josephson predicted remarkable phenomena that occur when two superconductors are weakly coupled together. The original paper dealt with coupling via a tunneling barrier but subsequent work showed that other means of weak coupling would give rise to the same governing equations. In particular, two superconductors separated by a "bridge" whose length and breadth are on the order of the superconducting coherence length, ξ, will form a Josephson system.[10] In these cases, a current, I, through the weak link is associated with a sinusoidal variation of the phase difference, ϕ, across the link.

$$I = I_c \sin\phi \tag{1}$$

In addition, if an electrochemical potential difference (per Cooper pair) $\mu = 2eV$ is applied across the link, the phase evolves in time as,

$$\frac{\partial\phi}{\partial t} = -\frac{\mu}{\hbar} \tag{2}$$

These two coupled equations give rise to numerous physical phenomena including quantum interference in a double weak link system, the so called SQUID: superconducting quantum interference device.

Due to the close analogy between superconductors and superfluids, scientists sought to develop superfluid weak links. Since the tunneling probability for an object as large as a helium atom is extremely small, the obvious candidate for a superfluid weak link is a coherence length size aperture joining two reservoirs of superfluid. In ^{4}He, the coherence length ξ_4 is on the order of only 0.1 nm, a length scale that is too small to manufacture an aperture or to give rise to observable phenomena. On the other hand, in ^{3}He, ξ_3

is on the order of 100 nm, a length scale within the realm of microfabrication technology and experimentally accessible currents. Single apertures and arrays of such apertures have been developed and studied both in Saclay and in Berkeley to demonstrate various weak link phenomena. A recent review of this work in given in Ref. 2.

Without repeating the details of Ref. 2 we mention here some of the main features revealed by recent experiments.

1. When the aperture size is on the order of ξ_3, the flow is governed by the two Josephson equations, (1) and (2) above, with pressure induced chemical potential difference (per Cooper pair) given by $\mu = 2m_3P/\rho$ where ρ is the liquid density and P the pressure difference.

2. The aperture's kinetic inductance is given by $L = \frac{\kappa}{2\pi}\frac{\partial\phi}{\partial I}$ (here κ is the quantum of circulation) and therefore, due to Eq. 1, depends on the instantaneous value of the mass current. When this weak link is coupled to a Hooke's law flexible membrane, the resultant oscillator is nonlinear.[11,12] In fact it was the nonlinear oscillator behavior first reported by Avenel and Varoquaux[11] that can be taken as the first positive observation of Josephson-like behavior in a ^{3}He weak link.

3. When a dc pressure head is applied across the weak link the mass current oscillates at the Josephson frequency,[13]
$$\omega_j = \frac{2m_3P}{\hbar\rho} = 184\,\text{kHz/Pa}. \tag{3}$$

4. When a combined dc and ac pressure head is applied to the weak link, the dc current is augmented when the frequency of the ac applied pressure matches the Josephson frequency associated with the dc pressure.[14]

5. At low temperatures where the aperture size is increased with respect to the coherence length the $I(\phi)$ function changes from that given by Eq. 1 to one characterized by a metastable state centered on π phase difference.[15]

6. Due to the vector nature of the superfluid order parameter, the weak link may exist in different metastable states, each with its own $I(\phi)$ function.[16]

7. A dc pressure head gives rise to non-ohmic dissipation which is predicted by a phenomenological model whose microscopic origins are as yet unclear.[17]

8. A double weak link device analogous to a dc SQUID, displays quantum interference effects. In particular the device's critical current can be cosinusoidally modulated by small rotations.[9] This superfluid SQUID shows promise as a very sensitive gyroscope.[18]

At the present time many aspects of superfluid weak links remain unknown. What is the nature of $I(\phi)$ at elevated pressures and in the A phase? What is the practical limit of sensitivity of a superfluid SQUID rotation sensor? Is it possible to induce phase shifts in the superfluid SQUID by interactions other than rotation? What is the microscopic explanation of the dissipation exhibited by the superfluid ^{3}He weak links? The answers to these existing questions and others await future experiments and theories.

3. PHASE SLIPS IN ^{4}HE

Superfluids can flow in a dc manner without any dissipation for small enough velocity. However there are mechanisms that limit the maximum fluid velocity to be less than some critical value. For instance ^{4}He superfluidity is limited to speeds less than about 55 m/s, the so-called Landau critical velocity[19] and ^{3}He superfluidity is limited by the depairing critical velocity. Early experiments showed that ^{4}He superflow is usually limited to speeds considerably less than the Landau critical velocity. P.W. Anderson explained this lowered critical velocity by invoking the concept of quantized vortices introduced by L. Onsager and R. Feynman. Anderson considered the superflow through an aperture (placed in a solid wall) and showed that if a quantized vortex passes across the aperture, energy will be passed from the aperture flow into the vortex flow. Each line passing across the aperture will change the quantum phase across the wall by 2π. These 2π phase slip events might be triggered by thermal activation processes[20] and if the flow is maintained by a pressure differential P, the 2π slips will occur at frequency,

$$\omega_j = \frac{m_4 P}{\hbar \rho} = 69\,\mathrm{kHz/Pa}. \tag{4}$$

This formula is the same as the Josephson frequency for the oscillating currents associated with a pressure biased weak link although the phenomenon it describes here has little to do with a "weak link" system.

The first observation of individual phase slip events was by O. Avenel and E. Varoquaux.[21] They constructed a superfluid oscillator by coupling a linear spring (a drumhead diaphragm) to the inertia of flow through a small slit aperture etched in a thin nickel foil. Using a sensitive displacement transducer to monitor the position of the diaphragm they could detect abrupt drops in the oscillation amplitude each time a phase slip occurred in the slit. Since their apparatus could determine the fluid velocity in the aperture at the moment of phase slippage their discovery led to a natural technique for studying the creation of quantized vortices (the origin of the phase slip) at the aperture's bounding surface.

Many experiments have been performed in Saclay, Minneapolis and in Berkeley studying and exploiting the phase slippage process. Much of this work is described in a recent review[1] and will not be detailed again here. Some of the most important results established by this technique are the following.

1. Quantized vortices are stochastically nucleated near the walls.
2. For temperatures above about 250 mK, thermal activation drives the nucleation.
3. For temperatures below 250 mK the vortices enter the system through a quantum tunneling process.
4. It is possible to make a sensitive rotation sensor using the phase slippage process to monitor rotation induced flow through an aperture. The device is an analog of the superconducting rf SQUID.

The experiments on phase slippage in ^{4}He have led to a great deal of clarification on the creation of quantized vortices and their role in superfluid dissipation. There are still several outstanding questions to be answered including: How are the phase slip vortices eventually converted into heat? What is the theory describing the quantum tunneling process? What are the practical limitations on rotation sensors based on the phase slippage process?

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REFERENCES

1. Richard Packard, *Rev. Mod. Phys.* **70**, 641–651 (1998).

2. J.C. Davis and R.E. Packard, *Rev. Mod. Phys.* **74**, 741–773 (2002).
3. J. Eisenstein, G.W. Swift and R. Packard, *Phys. Rev. Lett.* **43**, 1676 (1979).
4. I suspect he chose Berkeley for its excellent weather and its proximity to Oregon where, he discovered, he could purchase a Mercedes Benz automobile without paying any sales tax.
5. J.P. Eisenstein and R.E. Packard, *Phys. Rev. Lett.* **49**, 564 (1982).
6. H. Brand and M.C. Cross, *Phys. Rev. Lett.* **49**, 1959 (1982).
7. Lounasmaa et. al., *Phys. Rev. B* **28**, 6536 (1983).
8. G.W. Swift, J.P. Eisenstein and R.E. Packard, *Phys. Rev. Lett.* **45**, 1955 (1980).
9. R.W. Simmonds, A. Marchenkov, E. Hoskinson, J.C. Davis and R.E. Packard, *Nature* **412**, 55 (2001).
10. A.H. Dayem and C.C. Grimes, *Appl. Phys. Lett.* **9**, 47 (1966).
11. O. Avenel and E. Varoquaux, *Phys. Rev. Lett.* **55**, 2704 (1985).
12. A. Marchenkov, R.W. Simmonds, J.C. Davis and R.E. Packard, *Phys. Rev. B* **65**, 075414 (2002).
13. S.V. Pereverzev, A. Loshak, S. Backhaus, J.C. Davis and R.E. Packard, *Nature* **388**, 449 (1997).
14. R.W. Simmonds, A. Marchenkov, S. Vitale, J.C. Davis and R.E. Packard, *Phys. Rev. Lett.* **84**, 6062 (2000).
15. S. Backhaus et al, *Nature* **392**, 687 (1998).
16. A. Marchenkov et al. *Phys. Rev. Lett.* **83**, 3860 (1999).
17. R.W. Simmonds, A. Marchenkov, J.C. Davis, and R.E. Packard, *Phys. Rev. Lett.* **87**, 035301 (2001).
18. R.E. Packard and S. Vitale, *Phys. Rev. B* **46**, 3540 (1992).
19. For a review of superfluidity see D.R. Tilley and J. Tilley, *Superfluidity and Superconductivity* (Hilger, Bristol) (1990).
20. W.F. Vinen, *Proc. R. Soc. London*, Ser. A, **260**, 218 (1961).
21. O. Avenel and E. Varoquaux, *Jpn. J. Appl. Physics*, Suppl. **26**, 1798 (1987).